ADDITIVE MANUFACTURING OF THERMOPLASTIC COMPOSITES

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ABSTRACT

Ever since composite materials where first introduced, they have been pushing the boundaries of high performance, lightweight designs in all branches of engineering. The demand for sustainable lightweight structures results in an augmented use of thermoplastic composites. Depending on the type of matrix and reinforcement, there are various manufacturing options for the fabrication of composite parts. Composite manufacturing processes are in essence additive processes. In order to reduce the labor-intensive manual operations, and the need for a flexible automated composite process, researchers are investigating the feasibility of implementing Additive Manufacturing (AM) techniques to aid the fabrication of composite parts. AM techniques are able to produce parts directly from CAD data sources. As opposed to classical subtractive fabrication methods, parts are created layer upon layer. The geometric freedom provided by the additive process unlocks a wide variety of designs, which would be impossible to create via subtractive methods. Furthermore, AM processes have no direct need of tooling. The flexibility of this manufacturing approach gives rise to the development of application-oriented parts. Given the flexibility of the additive process, these techniques can be used in the design and manufacturing of composite parts. There are several options for which AM can be implemented in the composite production process. This paper highlights the potential of AM in the design and manufacturing of composite parts, gives a review on the application of composite AM, and identifies the technological challenges associated with the direct production of thermoplastic AM composites.

INTRODUCTION

Rapid Prototyping (RP) technology has received vast amounts of attention over recent years. The main advantage of this technique is its flexibility, enabling the development of application-oriented parts. Present research is predominantly focused towards the development of new materials and new processes to improve the structural integrity of RP parts. Industry reports indicate that RP or Additive Manufacturing (AM) is a resilient technology and one that has yet to reach its full promise, particularly in the field of composites. AM's impact on the composite industry has been difficult to gauge, but it is clear that several of the technologies offer opportunities to manufacturers of composite materials [1]. This paper highlights the developments made in the use of AM for the production of fiber reinforced thermoplastic parts. Composite manufacturing processes are in essence additive processes. The automated processes in particular, such as extrusion, automated tape placement (ATP) and automated fiber placement (AFP) show potential for use in an AM/composite hybrid process. This paper focuses on AM via extrusion-based techniques.

AM can be used to procure reinforced thermoplastic parts directly, via new composite materials. On the other hand, the flexibility of the technique allows for an indirect use of AM to facilitate composite production, in which AM components can aid composite manufacturing, speed up the production process, and enable the production of complex composite structures.

Rapid prototyping / Additive manufacturing

As the name suggests, the term rapid prototyping is used in a variety of industries to describe a process of rapidly creating a system or part representation before final release or commercialization [2].

Throughout the development of these rapid prototyping techniques, the name no longer fits the purpose, since the improvements in quality of the output of these techniques have meant there is a much closer link to the final product, the term “prototypes” seems deprecated. There is a common consensus to use the term Additive Manufacturing to summarize these techniques. AM describes a group of related technologies, which are able to produce physical models directly from Computer Aided Design (CAD) data sources. As opposed to classical subtractive methods, parts are created by the combination of materials layer upon layer. Each layer represents a slice of the part, derived from the CAD data source.

There are several benefits to the AM process. A key benefit of AM lies in the fact that AM processes are able to produce parts free of geometrical constraints, and provides complete flexibility in design and construction. The fact that materials are added rather than subtracted, results in a significant reduction of waste material. Furthermore, parts are built directly from a CAD model, without the direct need of application-specific tooling. This makes AM feasible for low-volume production of complex parts. The geometrical freedom means AM technologies are capable of producing freeform channels and lattice structures.

However promising the benefits may be, AM still faces several major challenges related to the production of fully functional parts. Depending on the AM technique, the layered manufacturing approach results in anisotropic mechanical properties of parts. Furthermore, there is a limited choice of available materials, and a limited accuracy and surface finish.

The AM process can be broken down into several steps. All AM parts must start from a virtual representation, which fully defines the external geometry by means of a solid body or a surface representation. Depending on the AM technique, a software-preprocessing step breaks down the 3D representation into cross-sections, depending on the layer resolution of the process. The thickness of these layers affects the overall quality of the end result. Each of these cross sections will be hatched with a certain pattern. This pattern defines the deposition strategy for each successive layer. The construction starts by uploading the patterns to the selected additive system. The build phase is mainly an automated process. For some techniques, a support structure is deposited to aid the manufacturing of the desired part. A post-processing step can be required to remove the aforementioned support structure [2].

ADDITIVE MANUFACTURING OF COMPOSITES

The use of AM technology has given rise to the development of application-oriented composites. Kumar and Kruth [3] have summarized the various AM techniques, which have been used for the production of composites. Composites are used in AM not only to make the desired product, but also to facilitate the process. The processes which have mainly been employed are: Selective Laser Sintering/Melting (SLS/SLM), Laser Engineered Net Shaping (LENS), Laminated Object Manufacturing (LOM), stereolithography (SL), Fused Deposition Modeling (FDM), Three Dimensional Printing (3DP) and ultrasonic consolidation [4,5,6]. AM techniques which have mainly been used with fiber-based composites, are SL, FDM and

LOM. In a powder-based AM technique such as SLS [7] and LENS, it is difficult to draw smooth layers of powder-fiber mixture [8]. Using long or continuous fibers instead of short fibers is difficult to incorporate into processing and its use has been limited solely to LOM and SL techniques [9,10]. In FDM and LOM, fabrication of respective fiber-reinforced composite filaments and laminates are required as a pre-step before RP processing, necessitating the need for materials to be formulated and developed [3]. The production of FDM grade composite material will be further discussed in the next section.

Gibson et al. have discussed how composite materials are included in a variety of different AM technologies, and have defined a classification of composite structures using AM technologies. A distinction is made between discrete interface composites, porous media composites and blended feeds [11].

Direct composite AM

This section discusses the use of extrusion-based techniques to directly produce composite components, using the AM principle to produce parts directly from CAD data sources.

Fused Deposition modeling

Fused Deposition modeling, pioneered by Stratasys Inc., has been the most widely adopted AM technique. In the fused deposition process, a spooled filament of a thermoplastic polymer is fed into a liquefier (***Figure1***), with the help of a pinch feed mechanism [2]. The incoming solid filament acts as a plunger to extrude the material through a circular nozzle in the form of a molten bead of material (also referred to as "roads") [12]. A constant volumetric displacement principle is applied upon deposition. The extruded polymer is deposited according to a fill pattern established by software pre-processing onto the build platform or previous layer. After the layer is finished, the build platform is lowered and the cycle repeats.

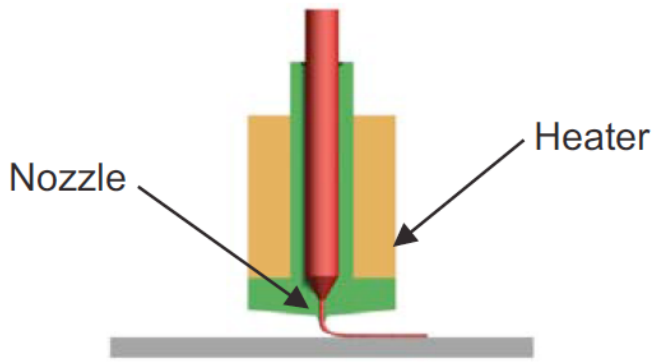

Figure1: Filament based deposition [24]

The AM process using the filament based extrusion technique of FDM requires the material to be processed into a filament form. This filament is produced by conventional polymer processing techniques, but this filament must be extruded to a very high diametric tolerance, which can't be achieved by conventional extruders [13,14].

As mentioned before, the incoming filament acts as a piston, pushing the molten material through the liquefier. Insufficient filament stiffness, or high viscosity can result in the buckling of the filament [12,15,16]. To avoid buckling, the applied extrusion pressure must be below a critical value [17,18]. Further drawbacks of this process are the potential slippage of the wire on the pinch wheel, causing an interruption of the building process [2,13,14].

Parts obtained from the FDM process are mostly used for model visualization and form/fit verification. In order to enhance the application range of FDM parts, new materials have been investigated to enable FDM to produce fully functional parts.

The mechanical properties of FDM parts can be enhanced, by incorporating a reinforcing material into the polymer matrix. Several attempts have been made to incorporate fibrous, metallic and ceramic filler materials into the feedstock filament for composite FDM processing [13,19,20]. This paper focuses on fiber reinforcement. The major challenge in enhancing the mechanical performance is the intralayer bonding strength between adjacent layers of material. The following section gives an overview of composite materials developed for the direct production of composites by FDM.

Composite FDM

In order to enable the mechanical properties of FDM parts, some research has gone into the development of thermoplastic composite materials, which can be used with existing, unmodified FDM equipment to produce high performance thermoplastic parts. This requires the production of reinforced thermoplastic filaments, which exhibit certain thermo-physical, mechanical, and layer-stacking characteristics. The requirements on thermo-physical properties include a proper range of melting and solidification temperatures, low coefficient of thermal expansion, minimal shrinkage, high heat resistance and no phase transformation in the solid state. On the one hand, the melting point should not be too low in order for the material to have a high softening point (or heat distortion temperature). On the other hand, the melting point should not be too high to avoid a high processing temperature [19].

Zhong et al. have experimentally produced a short glass fiber reinforced ABS (GFABS) polymer to use as a FDM feedstock material [19]. Initially, a commodity ABS polymer was used as the carrier for commercially available GFABS-30. Due to brittleness, the composition could not be made into filament form. A linear low-density polyethylene (LLDPE) was used to provide better ductility and flexibility. Due to phase separation between LLDPE and the ABS matrix, a compatibilizer was added to improve the linking between the molecular chains of ABS and LLDPE. This resulted in a GF reinforced filament with GF contents up to 18Wt%. It was proven that the addition of glass fibers resulted in a higher tensile strength under longitudinal loading. However, the addition of glass fibers adversely affected the adhesive strength between the layers in comparison to neat ABS. The adhesive strength between adjacent layers of GFABS did improve with the increasing GF content. It was speculated that a higher GF content provides a better chance for glass fibers to bridge together adjacent layers prior to the solidification of the ABS matrix. Limited research has been conducted on the effect of fibers on the bond formation between adjacent layers.

Shofner et al. have studied the application of reinforced thermoplastics containing carbon nanofiber and carbon nanotube as feedstock materials for FDM [20,21]. To produce enhancements in mechanical properties, even at lower concentrations of reinforcements, research was conducted concerning the alignment of the nanofibers within the polymer matrix. The presence of nanoparticles into polymer inhibits movement of polymer macromolecules and increases tensile modulus and strength of the polymer without reducing its impact resistance [8]. To obtain enhanced properties in these composite materials, the fibers should have a high degree of alignment as dictated by their high aspect ratios. The nanofiber dispersion and the degree of fiber alignment were investigated using a scanning electron microscope (SEM). There was a high degree of fiber alignment. This preferential fiber alignment produced an improvement in strength. However the composite specimens also showed a drastic decrease in elongation to failure as the fracture mode changed from ductile to brittle. While the intralayer strength had improved, the interlayer fusion was reduced.

Gray et al. have investigated the feasibility of using thermotropic liquid crystalline polymers (TLCPs) in a commercial FDM 1600 machine. The mechanical properties of some basic shapes were compared to parts created from neat ABS, produced by Stratasys. It was shown that the tensile moduli of 40Wt% TLCP reinforced PP composites where approximately 100% greater than those of ABS, and 150% greater than those of pure PP, considering identical lay-down patterns. While the interlayer strength did improve, the strength between adjacent layers and roads did not improve due to poor adhesion.

Process optimization

Current available AM techniques build up a part layer by layer. This flat layer approach inherently results in anisotropic properties of the produced parts. Within the flat-layer concept, only the fill-pattern and the build direction can be optimized for a specific component. The layered fabrication approach limits the use of fiber-reinforced composites, as these generally require a directional approach to design, with fibers running along the load direction or normal to the impact direction. This direction should relate to the required loads.

Chakraborty et al. have formulated a new method called Curved Layer FDM (CLFDM), with the focus on creating thin-section curved parts [22]. Singamneni et al. have developed algorithms for curved layer slicing based on practical solutions [23].
Curved layer AM uses a multi-axis system to enable additional complexity of motion. This enables the possibility of depositing a fiber-reinforced composite component using a directional design approach. The fibers can thus be positioned according to e.g. the natural stress distribution resulting from the natural loading of the modeled part. Especially for thin shell-like parts, curved layer slicing and deposition results in better material structure and consequent part strength, due to fiber alignment [23].

The major drawback of producing composite parts via FDM is the need to produce a reinforced polymer filament compatible with existing FDM equipment. This is not a trivial task, given the required characteristics of the filament. Valkenaers et al. have developed a novel screw based extrusion process. This process is able to extrude a wide variety of engineering thermoplastics, and uses polymer granulates directly as feedstock material [24]. This approach eliminates the required preprocessing of a fiber-reinforced filament feedstock, as compared to FDM.

Indirect composite AM

Depending on the type of matrix and reinforcement, there are various manufacturing options for the fabrication of composite parts. They range from using hand-layup, with labor and cost-intensive autoclave processing to the use of automated process such as extrusion, ATP and AFP. The need to reduce costs and cycle times while maintaining or improving quality and repeatability is a well appreciated challenge across manufacturing at large [25]. This section summarizes how AM can be effectively used to facilitate composite production. Given the highly flexible nature and geometric freedom of AM, custom produced parts can provide solutions for patterns, molds, preforms, intensifiers, layup tools, trim & drill tools, and even secondary processes like bonding fixtures. In addition to tooling, AM is also being successfully used for consumable cores that are being laminated or enveloped as an integral part of the final composite part.

The ability to combine solid modeling with a digitally mastered manufacturing process, which can produce everything from tooling to parts, enables new options for design, manufacturing and production. With these capabilities, companies can take advantage of the flexibility to rapidly respond to a wide range of needs. Today's composite manufacturing market is dynamic and demands new solutions [25].

FDM is often used in combination with carbon fiber and glass fiber layups. FDM parts are compatible with wet carbon-fiber layup as well as pre-impregnated carbon fiber layup [26].

Hollow composite parts present a unique manufacturing challenge. Straight-pull tube shapes and straight-walled cavities are easily addressed, but any configuration that traps the pattern, core or mandrel needs an alternative solution. FDM provides an efficient solution by means of a soluble core material [27]. The composite material is wrapped directly on a core that is dissolved away after the part has cured. This approach eliminates all tooling, which drastically reduced production time.

Automated thermoplastic composite manufacturing

The benefits of using thermoplastic over thermoset composites are well known, and the applications that use TPC will continue to grow. Several production processes have been developed with the general goal of automated production of high performance structures using thermoplastic composite materials. The most versatile of these technologies is in-situ consolidated TPC by automatic fiber placement, a true out-of-autoclave (OoA) AM process. The composite industry is progressing from labor- and cost intensive hand layup to automated processes [28]. Composites require additive processes, and in order to take advantage of the directional strength characteristics of composites, the fibers must be placed layer by layer in orientations and patterns that optimize their strength and stiffness for a given application [28]. The ideal manufacturing approach for composites would be a high performance additive manufacturing process that requires no post processing.

SUMMARY

Additive manufacturing technology has received a vast amount of attention over the last decade. Present research is predominantly focused towards the development of new materials and new processes to improve the structural integrity of AM parts. Incorporating reinforcing filler material to the polymer matrix can enhance the mechanical properties of these parts. It has been proven that the extrusion-based additive manufacturing techniques has a positive effect on the fiber alignment in the resulting parts. The main weakness of extrusion-based polymer AM parts is the interlayer bonding strength between adjacent layers. Further research is needed to identify the effects of fiber fillers on the bond formation of polymer filaments. The flat-layer based approach results in an inherent anisotropic property of the produced parts. Providing additional complexity of motion could enable custom application-oriented composites. Additive manufacturing techniques can facilitate the production of composites, but there is a need for a fully automated process to produce high-quality thermoplastic parts. Further research will investigate the effects of fiber-reinforcement on the bond formation between adjacent layers using an extrusion based AM process.

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